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RF ion heating near the lower hybrid frequency

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Wave absorption near the lower hybrid frequency is considered It is shown that in a hot plasma, a slow wave approaching the hybrid layer is strongly dampd by ion Landau damping

1. INTRODUCTION

One of the RF methods, which is often considered for supplementary ion heating in large Tokamak devices, is to use a slow wave with a frequency in the vicinity of the lower hybrid frequency The basic mechanisms, for energy transfer from the wave to the ions, which are usually invoked are the linear wave conversion (Stix 1965) and the less understood parametric effects (Porkolab 1974) In this note, we point out that in a hot plasma the external generated slow wave moving toward the hybrid layer, experiences strong linear Landau damping and is heavily absorbed at the conversion point

2 CALCULATION AND RESULTS

For propagation in the (x, z) plane, where x is the direction of the density gradient and z the direction of the confining magnetic field, the wave dispersion relation is

$$\lambda_T^2 k_x^4 - k_x^2 \epsilon_{rx} + k_z^2(\omega_{pe}^2/\omega^2) - i\epsilon = 0, \qquad \ldots \quad (1)$$

where

$$\lambda_T^2 \simeq 3V_i^2\omega^{-2}(\omega_{pi}^2/\omega^2), \quad \epsilon_{rx} = (\omega_{pi}^2/\omega^2)\,[(\omega^2/\omega^2_{LH}) - 1],$$

$$\epsilon = (\pi/2)^{\frac{1}{2}}\lambda_e^{-2}(\omega/|k_z|\,V_e)\exp(-\omega^2/2k_z^2V_e^2) + (\pi/2)^{\frac{1}{2}}\lambda_i^{-2}$$
$$\times(\omega/|k_x|\,V_i)\exp(-\omega^2/2k_x^2V_i^2),$$

and

$$V_\alpha^2 = T_\alpha/m_\alpha, \quad \lambda_\alpha = V_\alpha/\omega_{p\alpha}, \quad \omega_{LH}^2 = \omega_{pi}^2/(1+\omega_{pe}^2/\omega_{ce}^2)$$

and (Golant 1972),

$$n_z^2 = (ck_z/\omega)^2 \geqslant 1+\omega_{pe}^2/\omega_{ce}^2.$$

In the absence of damping eq. (1) yields

$$2\lambda_T^2 k_{(\pm)}^2 = \epsilon_{xx} \pm (\epsilon_{xx}^2 - 4k_z^2\lambda_T^2\omega_{pe}^2/\omega^2)^{\frac{1}{2}}. \qquad .. \quad (2)$$

For $\epsilon_{xx} \gg 2|k_z|\lambda_T\omega_{pe}/\omega$, $k^2_{(-)} \simeq k_z^2(\omega_{pe}^2/\omega^2)/\epsilon_{xx}$ and $k_{(+)}^2 \simeq \epsilon_{xx}/\lambda_T^2$. For $\epsilon_{xx} = 2|k_z|\lambda_T\omega_{pe}/\omega$, the two roots coincide, $k_{(+)}^2 = k_{(-)}^2 = k_c^2 = |k_z|(\omega_{pe}/\omega)/\lambda_T$, and the mode $(-)$ which is here the external generated wave, is converted (Moore 1972, Fidone 1974) into the mode $(+)$. Inserting eq. (2) in ϵ we have

$$(\epsilon/k_c^2) = (4\pi)^{\frac{1}{2}}(T_i/T_e)(\omega_{pi}^2/\omega^2)b[(2T_i/3T_e)^{\frac{1}{2}}b \exp\{-(2T_i/3T_e)^2 b\} +$$

$$+ (T_e/T_i)b^{\frac{1}{2}}\exp\left\{-\frac{b}{X\pm(X^2-1)^{\frac{1}{2}}}\right\}/\{X+(X^2-1)^{\frac{1}{2}}\}^{\frac{1}{2}}] \qquad .. \quad (3)$$

where

$$X = \epsilon_{xx}/2|k_z|(\omega_{pe}/\omega)\lambda_T - (b/3)[(\omega/\omega_{LH})^2 - 1]$$

$$b^2 = (3T_e/4T_i)(\omega/k_z V_e)^2 \gg 1$$

We see from eq. (3) that the ion damping dominates the electron damping if

$$b > (3T_e/2T_i)/[X + (X^2-1)^{\frac{1}{2}}] \qquad . \quad (4)$$

We assume that eq. (4) is fulfilled and in eq. (3) we ignore the electron term. At $X = 1$ we have

$$(\epsilon/k_c^2) = (4\pi)^{\frac{1}{2}}(\omega_{pi}^2/\omega^2)b^{3/2}\exp(-b) \qquad . \quad (5)$$

where $(\omega_{pi}^2/\omega^2) = (1+\omega_{pi}^2/\omega_{ce}^2)(1+3/b)$. For the typical Tokamak parameters,

$$T_e = 2\,\text{keV},\ T_e/T_i = 2,\ \omega_{pe} = \omega_{ce} = 5{\cdot}6\times10^{11}\ \text{sec}^{-1}\ n_z = 2,$$

we have $b = 10$ and $(\epsilon/k_c^2) = 8\times10^{-3}$. This corresponds to a strong dissipative effect and the mode $(-)$ is totally absorbed before reaching the point $X = 1$. In this case we ignore the mode $(+)$. We now discuss the damping of the backward mode $(-)$. Letting $k_r = -k + i\tilde{k}$ in eq. (1) we obtain

$$k^2 - \tilde{k}^2 = \frac{2k\tilde{k}\,\epsilon_{xx} - \epsilon}{4\lambda_T^2 k\tilde{k}} \qquad .. \quad (6)$$

$$4\lambda_T^4(4k^2\tilde{k}^2)^2 + (4k^2\tilde{k}^2)[\epsilon_{xx}^2 - 4k_z^2\lambda_T^2\omega_{pe}^2/\omega^2] - \epsilon^2 = 0$$

where ϵ is given by eq. (3). Letting

$$32\lambda_T^4B^2 = [(\epsilon_{xx}^2 - 4k_z^2\lambda_T^2\omega_{pe}^2/\omega^2)^2 + 16\lambda_T^4\epsilon^2]^{\frac{1}{2}} - (\epsilon_{xx}^2 - 4k_z^2\lambda_T^2\omega_{pe}^2/\omega^2), \qquad .. \quad (7)$$

from eqs. (6) we obtain

$$k\tilde{k} = B,\quad 2k^2 = \left[\left(\frac{2B\epsilon_{xx}-\epsilon}{4\lambda_T^2 B}\right)^2 + 4B^2\right]^{\frac{1}{2}} + \frac{2B\epsilon_{xx}-\epsilon}{4\lambda_T^2 B} \qquad ... \quad (8)$$

From eqs (7) and (8) we obtain the two limits

$$2(k/\tilde{k}) \simeq (4\pi/9)^{1/2} b^{5/2} \exp\left[\frac{-b}{X-(X^2-1)^{1/2}}\right] / [X-(X^2-1)^{1/2}]^{3/2}(X^2-1)^{1/2}, \quad \ldots \quad (9)$$

where $X^2-1 \gg (2/3)(4\pi)^{1/2} b^{5/2} \exp(-b)$ and k is given by eq (2) and

$$2(\tilde{k}/k_c) = [(4\pi/9)^{1/2} b^{5/2} \exp(-b)]^{1/2}, \; k \simeq k_c, \quad \ldots \quad (10)$$

for $X = 1$ We note that eq (10) is obtained from eq. (9) for $X^2-1 = (4\pi/9)^{1/2} b^{5/2} \exp(-b)$ In a homogeneous portion of the plasma the wave energy damping is described by the factor $\exp(-2\tilde{k}x)$ We assume that total absorption takes place if $\tilde{k}x \sim 1$

From eqs (9) and (10) we obtain

$$(\lambda_0/x) = (2\pi/3)^{3/2} n_z (m_i/m_e)^{1/2} b^3 \exp\left[-\frac{b}{X-(X^2-1)^{1/2}}\right] / [X-(X^2-1)^{1/2}](X^2-1)^{1/2}, \ldots \quad (11)$$

$$(\lambda_0/x) = (2\pi/3)\pi^{1/4} n_z (m_i/m_e)^{1/2} b^{7/4} \exp(-b/2). \quad \ldots \quad (12)$$

where λ_0 is the vacuum wavelength For $b = 10$, $n_z = 2$ $(m_i/m_e)^{1/2} = 43$ from eq (12) we have $x = \lambda_0/90 \simeq 0{\cdot}2$ cm Using eq. (11) it is easy to see that the absorption process is highly localized In conclusion, we have shown that in a hot plasma a slow wave is completely absorbed by the ions at the resonance defined by $(\omega/\omega_{LH})^2 = 1+3/b$

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